

What can WMAP tell us
about the very early universe?

New Physics as an explanation of:

- suppressed large scale power
and
- running spectral index

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WMAP found two surprising results:

Cosmic microwave background spectrum of anisotropies has

- 1) unexpected low power on very large scales (low-" l " modes)
- 2) running of the spectral index of density perturbations

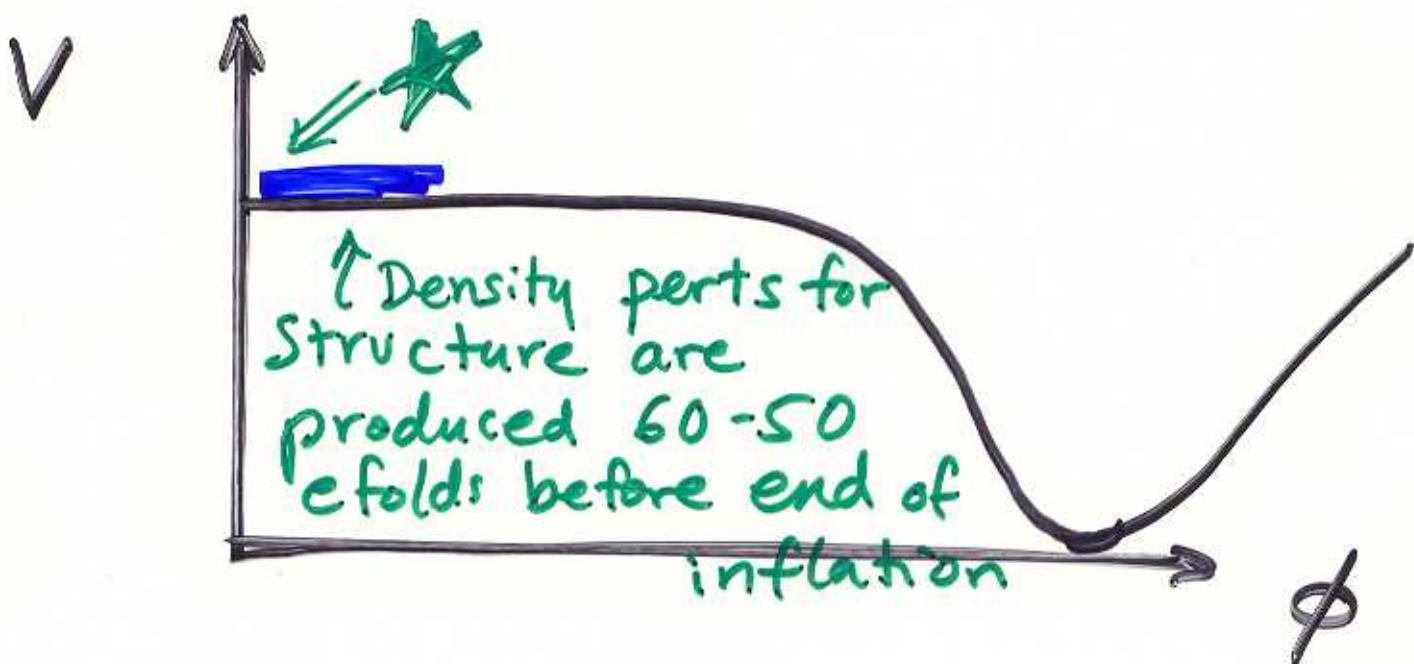
3 questions about interpretation of the data :

cosmic variance ?

priors ?

Possible Explanation:

We could be learning about the "initial conditions" for the part of inflation that gives rise to observables in structure formation + CBR



This could be determined by new physics, which is the relevant theory valid at scales $\gtrsim E_c$, the cutoff scale of effective low energy theories.

We will study two examples,

- modified Friedmann eqns
- velocity dependent potentials

that may have resulted from a deeper underlying theory (e.g. string theory) and that can explain these 2 data anomalies.

How Much Fine Tuning is Needed?

E.g. 1: modifications to Friedmann eqn

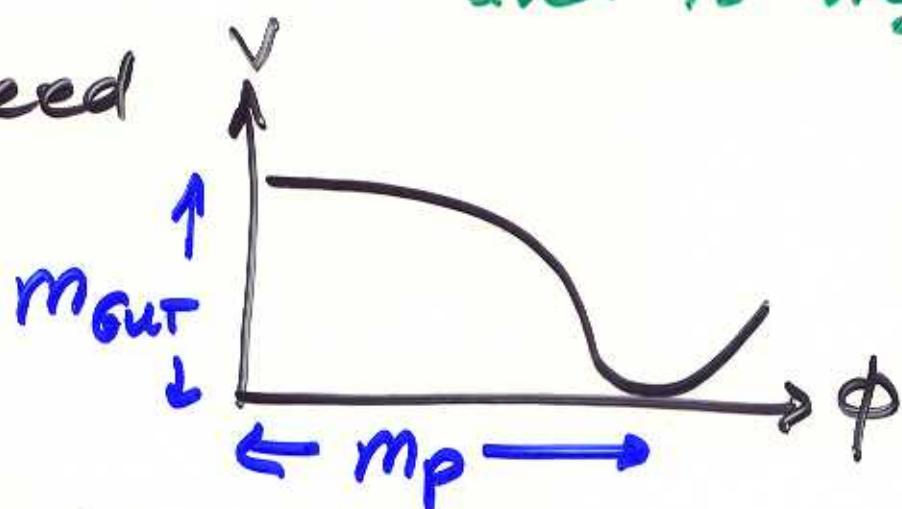
$$H^2 = \frac{8\pi}{3m_p^2} (\rho + f[\rho])$$

e.g. Randall-Sundrum (RS1)

$$H^2 = \frac{8\pi}{3m_p^2} \left[\rho + \frac{\rho^2}{2\sigma} \right]$$

where σ = brane tension
and is negative

We need



$$|\sigma|^{1/4} \sim V^{1/4} \sim [10^{-3/4} M_p]$$

Then 2nd term becomes important for $\rho \gtrsim \sigma$,
i.e. at beginning of inflation

$$\text{Since } M_p^2 = \frac{3}{4\pi} \left(\frac{M_5^2}{|\sigma|} \right) M_5 \Rightarrow M_5^{3/2} \sim M_p/20$$

Randall-Sundrum

$$H^2 = \frac{\Lambda_4}{3} + \left(\frac{8\pi}{3M_p^2} \right) \rho + \left(\frac{4\pi}{3M_5^3} \right)^2 \dot{\rho}^2 + \frac{\epsilon}{a^4}$$

choose bulk

$$\Lambda_5 \sim -4\pi G^2/3M_5^3$$

$$\text{s.t. } \Lambda_4 \sim 0$$

not important
during inflation

Basic Mechanism :

Density fluctuations well below today's horizon scale are unaltered.

Fluctuations on large scales are suppressed. WHY?

New physics, at scales $\ell \gtrsim \Gamma$, causes breakdown of slow-roll \Rightarrow

K.E. of ϕ field $\gg V \Rightarrow$

no density fluctuations produced.

Once $V \sim \Gamma$, slow roll begins,
at ~ 60 efolds before end of inflation.
Density flucs produced as usual.

This mechanism relies on having the scale of new physics $E_C = \Gamma^{1/4}$
exactly at height of potential 60
efolds before end. [i.e. $M_S^{3/2} \sim M_P/20$]
Given this, K.E. domination above E_C
follows automatically + produces low- ℓ modes

Contaldi, Peloso,
Kofman, Linde

A similar proposal

also invokes the failure of SR
60 e-folds before end of inflation.
How? a change in the shape
of a hybrid inflation potential
exactly at the right time
to get suppression.

Fine-tuning: potential or
initial conditions must be
carefully chosen.

VS. our fine-tuning:
We do NOT require any special
features of the potential, which
can be ordinary. Instead,
we pick scale of new physics
(e.g. for modified Friedmann eqns)

The CBR spectrum from modified FRW:

$$H^2 = \frac{8\pi}{3m_p^2} (\rho + f(\rho))$$

Here $\rho_{\text{tot}} = \rho + p_f$, where

$$p_f = (\rho + p) \frac{df}{d\rho} - f(\rho)$$

Power spectrum today

$$\frac{k^3}{2\pi} P(k) = \left(\frac{k}{aH_0} \right)^4 T^2(k) \delta_H^2(k)$$

↑ transfer fn. | at ↑ horizon crossing

We'll take usual

$$\delta_H = \frac{\delta s}{\rho + s} \Big|_{k=aH}$$

$$\delta_H \approx \left(\frac{H}{2\pi} \right) \left(\frac{-v'}{\frac{M_p^2}{4\pi} \dot{H} + f(\rho) + p_f} \right)$$

The spectral index

$$n_s - 1 = \frac{d \ln \delta_H^2}{d \ln k}, \quad \delta_H^2 \propto \left(\frac{k}{k_s} \right)^{n_s - 1}$$

$$\text{Then, } \delta_H^2 = \delta_H^{(0)2} \stackrel{\text{unmodified}}{\leftarrow} g(\phi)$$

$$\text{where } g(\phi) = \frac{1}{[1 + 4\pi(f(r) + p_f)/M_p^2 H]^2}$$

$$\text{Hence } (\eta_S - 1) = (\eta_S^{(0)} - 1) + \frac{d\log}{d\ln k} = (\eta_S^0 - 1) + f n_S$$

$$g(\phi) = \left(\frac{k}{k_S}\right)^{f n_S}$$

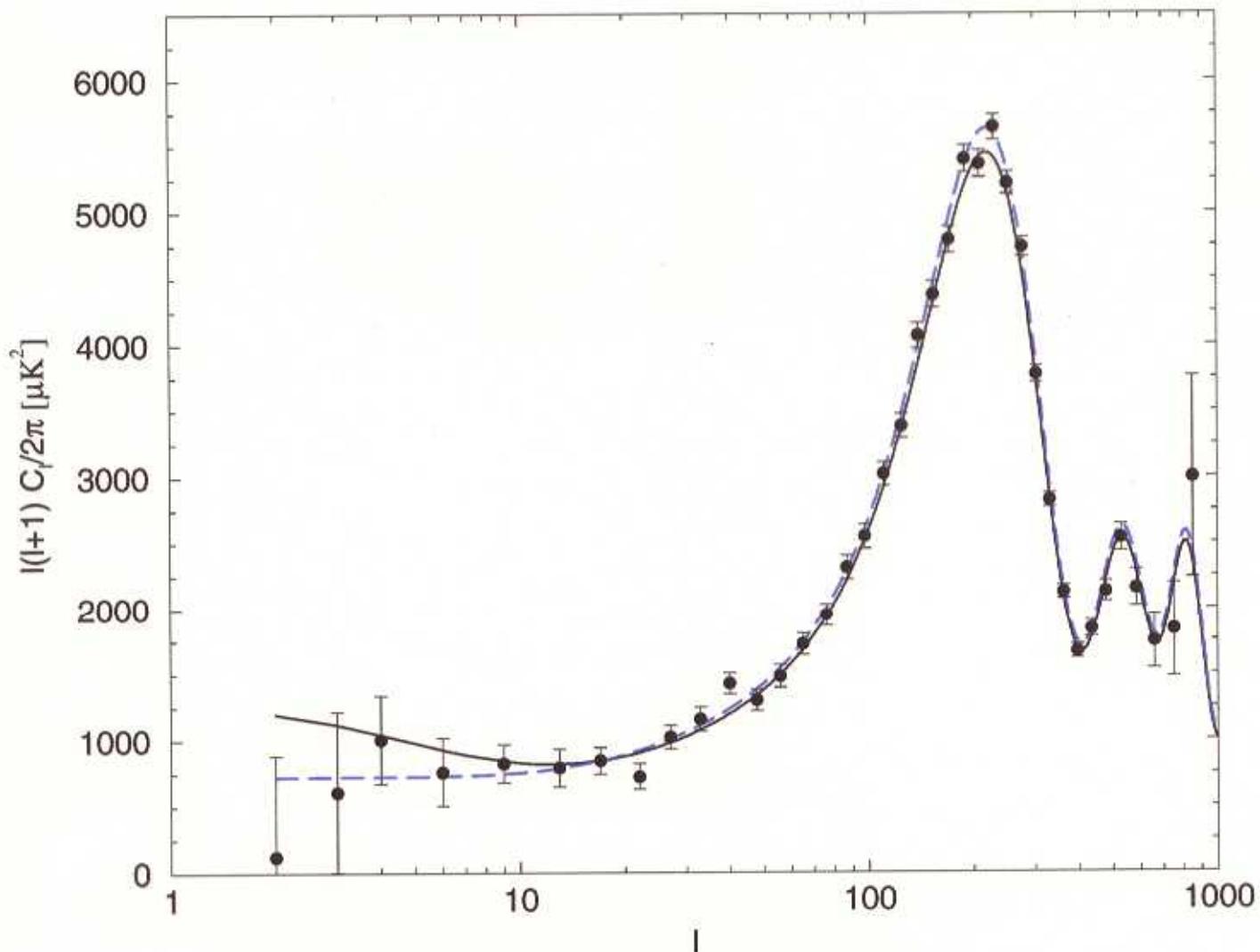
Very Roughly

$$\delta_H^2 = \delta_H^{(0)2} \left[1 - e^{-\left(\frac{k}{k_1}\right)^{f n_S}} \right]$$

CBR spectrum of Anisotropies

modified curve: $\delta n_s = 1$, $k_s = 0.0005 \text{ Mpc}^{-1}$

generated w/ CMBFAST



Back to Randall-Sundrum:

$$\delta_H < \delta_H^{(0)} \text{ when } g^2/|\sigma| \geq g \begin{cases} \text{NO} \\ \text{SLOW} \\ \text{ROLL} \end{cases}$$

$$\delta_H \rightarrow \delta_H^{(0)} \text{ when } g^2/|\sigma| < g$$

$$H^2 = \frac{8\pi}{3M_p^2} g \left[1 + \frac{g}{2\sigma} \right]$$

$$= \frac{8\pi}{3M_p^2} V \left[1 - \frac{V}{2|\sigma|} \right]$$

when $\vec{g} = \vec{V}$

For slow-roll epoch,

$$\delta_H^2 \sim \left(\frac{512\pi}{75M_p^6} \right) \frac{V^3}{V^{1/2}} \left[1 - \frac{V}{2|\sigma|} \right]^3$$

Concrete example of a potential:

$$V = V_0 e^{-\lambda\phi}$$

Concrete e.g. of a potential :

$$V = V_0 e^{-\lambda \phi}$$

We find

$$\delta_H^2 \sim 8\pi \left(\frac{512}{75 M_P^4} \right) \frac{V_0}{\lambda^2} \left[\frac{k}{k_S} \right]^{\frac{n_S - 1}{1 - V_0/2|\sigma|}} \tilde{g}(\phi)$$

$$\text{where } \tilde{g}(\phi) = \left[1 - \frac{V_0}{2|\sigma|} \left(\frac{k}{k_S} \right)^{\frac{n_S - 1}{1 - V_0/2|\sigma|}} \right]^3$$

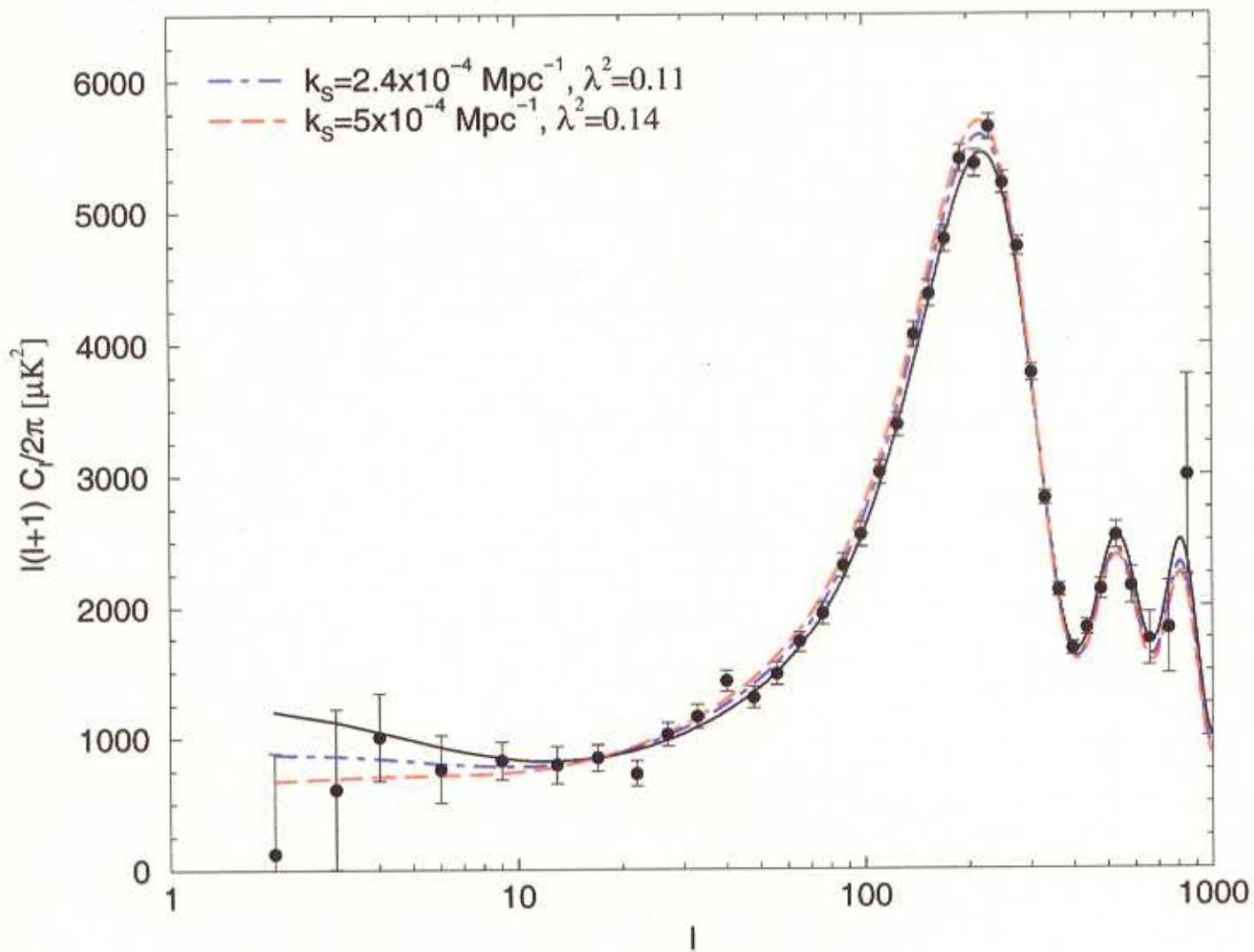
Use CMBFAST,

normalize to WMAP $\ell=17$

Modified CBR Spectrum

$$n_s^0 - 1 = -\lambda^2$$

k_s corresponds to scale of perts.
produced 60 e-folds before
end of inflation, i.e.
 $k_s^{-1} \sim$ horizon size today.



Running Spectral Index

from WMAP: $\{ \begin{array}{l} n_s > 1 \text{ (blue) on large scales} \\ n_s < 1 \text{ (red) on small scales} \end{array} \}$

Chung, Shiu, + Trodden proposed a carefully chosen potential whose slope reaches a minimum where spectral behavior changes.

We find: modified Friedmann eqns also give this running:

δH^2 increases with k for small scales

δH^2 decreases " large "

$$\text{with } k_{\max}/k_s = \left[\frac{|v|}{2V_0} \right]^{\frac{1}{n-1}}$$

$$\text{where } \tilde{n}-1 = n_s^0 - 1$$

$$\text{For } V_0 = |v| + \lambda^2 = 0.11, \quad \frac{1-V_0/2}{1-V_0/2} |v|$$

$$k_{\max}/k_s = 23 \Rightarrow \text{MAX POWER at } 180 \text{ Mpc}$$

Another eg. of new physics :

Velocity - Dependent Potentials

Shiu + Tye: branes moving wrt each other

$$V(\phi) \propto \dot{\phi}^p / \phi^q$$

effective action :

$$\Gamma(\phi) = \int d^4x \left[-a^3 V(\phi) + \frac{1}{2} a^3 Z(\phi) \dot{\phi}^2 - \frac{1}{2} a Z(\phi) (\nabla\phi)^2 \right]$$

Same form
as
we did
before

$$\delta_H = \delta_H^{(0)} Z(\phi) \quad \text{with} \quad \delta n_S = n_S - n_S^0 = 2 \frac{d \ln Z}{d \ln k}$$

Signatures: modified tensor/scalar ratio

low- ℓ suppression

$$\text{e.g. } Z(\phi) = 1 - V(\phi) / E_C$$

Again, convection term blows up at $V_0 = E_C$

thus violating slow-roll and
introducing cutoff in spectrum ~~at~~
 $\delta_H \rightarrow 0$

$$f_{ns} = \frac{2V^2}{3H^2 E_c (1 - \frac{V}{E_c})^2}$$

For $V = V_0 e^{-\lambda \phi}$

$$f_{ns} = 2\lambda^2 (V_0/E_c) \left(\frac{k}{k_s}\right)^{\frac{d^2}{1-V_0/E_c}} \times$$

$$\frac{1}{\left[1 - (V_0/E_c) \left(\frac{k}{k_s}\right)^{\frac{d^2}{1-V_0/E_c}}\right]^2}$$

Observational data can
discriminate between models

Summary

Two anomalies in WMAP data

- (- low " l " modes suppressed
- running spectral index

may point to "new physics"
at the beginning of inflation.

We studied two examples

- modified Friedmann eqns.
- velocity dependent potentials

that ~~be~~ may have resulted
from a deeper underlying theory,
e.g. string theory,

We found that both anomalies
in the data may be
explained.